SEMICONDUCTOR LASER DEVICE

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a semiconductor laser device, and more specifically, to a semiconductor laser device adapted for use as a pumping light source for optical fiber amplifier, such as a laser device of the gain-waveguide type that oscillates with a wavelength of, e.g., 0.98 μm and requires high optical output of hundreds of mW, and capable of ensuring a linear current-optical output characteristic even during high-current operation.

Prior Art

In a semiconductor laser device that has an active layer (quantum region) formed of a quantum well structure, injected carriers are quantized toward quantum wells, and the state density of carrier energy is stepped. Accordingly, the gain coefficient suddenly rises in response to driving current, so that a laser beam can be oscillated even with use of a low threshold current density. The semiconductor laser device of this type delivers higher optical output than a semiconductor laser device that includes an active layer of a bulk semiconductor, so that it is being studied for practical use as a pumping light source for optical fiber amplifier.

For example, the following semiconductor laser device that oscillates with a wavelength of 0.98 μm is an object of investigation as a pumping light source for optical fiber amplifier. This device will now be described with reference to the accompanying drawings.

FIG. 1 is a side view showing the semiconductor laser device, and FIG. 2 is a sectional view taken along line II-

II of FIG. 1.

The device has a layer structure of a semiconductor material, including a lower clad layer 2 of n-AlGaAs, an active layer 3 of a quantum-well structure made of InGaAs and GaAs, an upper clad layer 4 of p-AlGaAs, and a cap layer 5 of p-GaAs, which are stacked in layers on an n-GaAs substrate 1. A part of the upper clad layer 4 and the cap layer 5 form a mesa structure, and a passivation film 6 of SiN is formed on the lateral of the mesa structure. Further, an upper electrode 7 of Ti/Pt/Au is formed on the cap layer 5 and the passivation film 6, and a lower electrode 8 of AuGe/Ni/Au is formed on the back surface of the substrate 1.

The device A is manufactured in the following manner. The aforesaid layer structure is formed on the n-GaAs substrate by, for example, the MOCVD method, and the upper and lower electrodes are formed on the upper and lower surfaces, respectively, of the layer structure. Thereafter, the resulting structure is cleft with a given cavity length L, a low-reflection film 9 of, e.g., SiN is formed on one end face (front facet) S_1 of the structure, and a high-reflection film 10 of, e.g., SiO_2/Si is formed on the other end face (rear facet) S_2.

In the case of the device A having this mesa structure, it is believed that high optical output can be effectively obtained by increasing the cavity length L. This is because if the cavity length L increases, the influence of heat can be lessened, so that high-optical output can be expected. If the cavity length is too long, however, the differential quantum efficiency of the device A lowers, so that higher current is required for high-optical output operation. Normally, therefore, the cavity

length L of the device A with this construction is designed so that the cavity length L is not longer than 1,000 μm.

The inventors hereof examined the current-optical output characteristic for the case where the cavity length L of the device A with the layer structure shown in FIGS. 1 and 2 was adjusted to 800 μm. Thereupon, the characteristic curve of FIG. 3 and the following new knowledge were obtained.

When a driving current (A_1) of about 200 mA was injected, as seen from FIG. 3, a first kink (a_1) was generated in the optical output, and the existing linear relation between the driving current and the optical output disappeared. If the driving current was further increased to a level (A_2) of about 500 mA, a second kink (a_2) was generated in the optical output. Thus, in the case of the device A, the two kinks a_1 and a_2 were generated in the current-optical output characteristic curve as the driving current was increased.

Accordingly, the inventors hereof first closely examined the oscillation spectrum of the device A. The following is a description of the results of the examination.

(1) FIG. 4 shows an oscillation spectrum obtained when the injected current was at about 200 mA.

As seen from this oscillation spectrum, there is a small number of longitudinal modes which oscillate actually in a gain band g. The intensity of a central longitudinal oscillation mode B_0 is 5 dB or more higher than those of side modes B_1 and B_2. As a whole, single longitudinal mode oscillation that is prescribed by the central longitudinal oscillation mode B_0 is dominant.

(2) An oscillation spectrum obtained when the first

kink (a_1) was generated indicates that the central longitudinal oscillation mode B_0 jumps to the side mode B_1 at a distance of about 0.4 nm therefrom when the gain band shifts to the longer wavelength side as the temperature of the device rises with the increase of the injected current.

The probability of generation of single longitudinal mode oscillation is related to a spontaneous emission factor (βsp) given by

$$\beta sp = \Gamma \cdot \lambda^4 \cdot K / 4\pi^2 \cdot n^3 \cdot V \cdot \delta\lambda, \quad \cdots (1)$$

where Γ is the confinement coefficient of the active layer, λ is an oscillation wavelength, K is a factor reflective of the complexity of the electric field for a transverse mode, n is an equivalent refractive index, V is the volume of the active layer, and δλ is the half width of the spontaneous emission spectrum. It is believed that the smaller the value βsp, the higher the probability of generation of single longitudinal mode oscillation is.

In the case of the device A, therefore, the oscillation wavelength (λ) is as short as 0.98 μm, so that βsp is lowered in proportion to the fourth power of λ. Accordingly, the device A can be supposed to be able to cause single longitudinal mode oscillation with high probability.

The following problem will be aroused, however, if a module is constructed in a manner such that the device A that undergoes single longitudinal mode oscillation is connected to an optical fiber. A laser beam generated by single longitudinal mode oscillation has its noise properties lowered under the influence of return light from an end portion of the optical fiber. Further, the oscillation of the laser beam is made unstable by the return light. Accordingly, an optical output fetched from

the module and monitor current are rendered unstable.

In order to use the device A as a reliable pumping light source for optical fiber amplifier, therefore, it is necessary to solve the above problem that is attributable to single longitudinal mode oscillation.

The result (2) implies the following situation. In consideration of gain differences caused between the longitudinal modes for single longitudinal mode oscillation for the aforesaid reason, the longitudinal mode hopping occur which causes substantial discontinuous fluctuations of the optical output when the gain band shifts to the longer wavelength side in response to temperature rise. When the injected current almost reaches the level A_1, therefore, the current-optical output characteristic loses its linearity, so that the first kink (a_1) is generated.

Then, the inventors hereof observed a far field pattern of the device A and obtained the findings shown in FIG. 5.

In FIG. 5, curve C_1 represents a transverse oscillation mode for the case where the injected current is lower than A_2, and curve C_2 represents a transverse oscillation mode for the case where the injected current is near A_2 (or where the second kink a_2 is generated).

If the injected current increases to A_2, as seen from FIG. 5, unit-modal transverse oscillation modes shift horizontally from the center position of the device A (or undergo beam steering). Thus, the direction of emission of the laser beam changes.

In the case where the module is constructed by connecting the ~~optical fiber~~ to the device A, therefore, the optical output fetched through ~~the optical fiber~~ fluctuates when the injected current reaches a value

approximate to A_2. This is supposed to result in the generation of the second kink (a_2) in the current-optical output characteristic curve.

OBJECT AND SUMMARY OF THE INVENTION

An object of the present invention is to provide a semiconductor laser device of the gain-waveguide type, capable of oscillating in a longitudinal multi-mode without generating any kinks in a current-optical output characteristic curve even with use of an injected current of 500 mA or more.

Another object of the invention is to provide a novel semiconductor laser device adapted for use as a high-reliability pumping light source for optical fiber amplifier and connected to an optical fiber to form a module, in which a bad influence of return light can be restrained and there is no possibility of beam steering in a far field pattern, so that fluctuations of fetched optical output can be inhibited.

The inventors hereof conducted the following examinations in the process of investigation to achieve the above objects. These examinations will be described first.

(1) First, single longitudinal mode oscillation occurs with high probability in the case of a semiconductor laser device that oscillates in a short-wavelength band of about 0.98 μm. If the injected current increases, the longitudinal mode hopping occurs which causes substantial fluctuations of the optical output. This results in the development of a first kink (a_1) in a current-optical output characteristic curve.

It is known that the intervals between the longitudinal modes are proportional to the reciprocal of

the cavity length (L) of the device. Therefore, the intervals between the longitudinal modes can be shortened by increasing the cavity length (L) of the device, so that fluctuations of the optical output caused by the jumping of the longitudinal modes can be reduced, supposedly.

(2) Further, a shift of transverse oscillation modes (beam steering) that causes a second kink (a_2) is a phenomenon that takes place from the following cause. As the injected current increases, rise of the temperature is accelerated by resistance heating. The refractive index of a region near the active layer is increased by the thermal lens effect, so that the distribution width of light in the horizontal direction is reduced. Accordingly, the carrier density of a light distribution area is lowered by spatial hole burning of carriers, so that the refractive index increases further. In the end, the refractive index distribution in the horizontal direction is disturbed, so that the transverse light confinement effect is lowered.

In order to prevent the generation of the second kink, therefore, it may be advisable to design the device (cavity) so that its resistance heat is small even when high current is injected. To attain this, it is necessary only that the cavity length of the device be increased to lower the resistance of the device.

(3) If the cavity length (L) of the device is increased, in this case, the quantum efficiency lowers inevitably. However, this can be avoided by using a low-reflection surface as the quantum surface of the device.

In consideration of these circumstances, the inventors hereof varied the cavity length (L) of the device A and examined the current-optical output characteristic of the device. Thereupon, the inventors found that the

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linearity of the current-optical output characteristic curve can be secured by adjusting the cavity length (L) to a value not smaller than the value mentioned later, and developed the semiconductor laser device according to the present invention.

Thus, according to the invention, there is provided a semiconductor laser device comprising: a laminated structure of a semiconductor material including an active layer formed of a quantum well structure; a low-reflection film formed on one end face of the structure; and a high-reflection film formed on the other end face of the structure; and the cavity length of the device being 1,200 μm or more.

Preferably, the device has a transverse light confinement structure with the transverse refractive index difference of about 1×10^{-2} for oscillation modes, the reflectance of the low-reflection film on the one end face is 5% or less, and the active layer is formed of one or two quantum well structures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side view of a laser device A of the gain-waveguide type;

FIG. 2 is a sectional view taken along line II-II of FIG. 1;

FIG. 3 shows a current-optical output characteristic curve for the device A of FIG. 1 (for the case of the cavity length of 800 μm);

FIG. 4 shows an oscillation spectrum of the device of FIG. 1;

FIG. 5 is a graph showing transverse modes for a far field pattern of the device of FIG. 1;

FIG. 6 is a graph showing the relation between the cavity length (L) of the device and the current value for the generation of a kink (a_1);

FIG. 7 is a graph showing the relation between the cavity length (L) of the device and the current value for the generation of a kink (a_2);

FIG. 8 shows an oscillation spectrum of a device according to the invention with the cavity length of 1,500 μm; and

FIG. 9 shows a current-optical output characteristic curve for the device of the invention with the cavity length of 1,500 μm.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A device according to the present invention will now be described with reference to a device A shown by FIGS. 1 and 2.

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The device of the invention has a layer structure such that a semiconductor material is put on a semiconductor substrate by, for example, the MOCVD method, and an active layer 3 is formed of a quantum well structure. InP- and GaInNAs-based semiconductor materials may be used in place of ~~the aforesaid materials for~~ the device A.

The most distinguishing feature of the device of the invention lies in the cavity length (L) of 1,200 μm or more.

If the cavity length (L) increases, the intervals between the longitudinal modes which oscillate in the gain band of the oscillation spectrum are shortened in proportion to the reciprocal of the cavity length, as mentioned before. If the cavity length (L) is 1,200 μm or more and if the quantum well structure is formed of InGaAs/GaAs, the interval between each two adjacent

longitudinal oscillation modes is about 0.12 nm spacing. This oscillation spectrum shows a longitudinal multi-oscillation mode in which a large number of longitudinal oscillation modes aggregate densely at short intervals in the gain band.

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In the case of a module that is formed by connecting an optical fiber to the aforesaid device, therefore, return light from the optical fiber is also based on the longitudinal multi-mode, so that oscillation of a laser beam can be restrained from being made unstable by the return light.

In this longitudinal multi-oscillation mode, moreover, gain differences between the longitudinal modes are so small that fluctuations of the optical output are small even if the longitudinal modes jump. In consequence, the first kink (a_1) ceases to be generated in the current-optical output characteristic.

In order to obtain more stabilized the longitudinal multi-oscillation mode, the volume of the active layer that is formed of the quantum well structure should preferably be reduced. More specifically, it is advisable to use one or two quantum well structures to form the active layer.

If the volume of the active layer is reduced, the value βsp in expression (1) becomes greater, so that single longitudinal mode oscillation is restrained. If the active layer volume is lessened, moreover, the internal loss of the cavity is reduced, so that the optical output can be improved.

If the cavity length (L) is 1,200 μm or more, furthermore, the volume resistance of the cavity is lowered. If the injected current is increased, therefore, the temperature of the active layer is restrained from rising,

so that the laser beam no longer can be moved. In consequence, dislocation of transverse oscillation modes (beam steering), which occurs with conventional devices, never takes place, so that the second kink (a_2) cannot be generated in the current-optical output characteristic.

Thus, in the case of the device according to the present invention, the cavity length (L) is adjusted to 1,200 μm (or more), so that the kinks a_1 and a_2 cannot be generated in the current-optical output characteristic curve, and therefore, the linearity of the curve can be maintained.

Since the increase of the cavity length (L) results in a reduction of the quantum efficiency, however, a low-reflection film should preferably be formed on one end face (front facet) of the cavity in the device of the invention.

More specifically, a low-reflection film with a reflectance of 5% or less is formed on the one end face of the cavity, and a high-reflection film with a reflectance of 80% or more on the other end face.

[Example]

1. Manufacture of Device

A lower clad layer 2 of n-AlGaAs with a thickness of 2 μm, an active layer 3 formed of two quantum well structures of InGaAs and GaAs, an upper clad layer 4 of p-AlGaAs with a thickness of 2 μm, and a cap layer 5 of p-GaAs with a thickness of 0.3 μm were successively stacked in layers on the (100) surface of an n-GaAs substrate 1 by the MOCVD method. Thereafter, the upper part of the resulting layer structure was formed into a mesa structure 4 μm wide and 2 μm high, and its whole surface was coated with a passivation film 6 of SiN. The back surface of the substrate 1 was polished so that the overall thickness of

the substrate was about 100 μm. After that portion of the passivation film 6 which was situated on the upper surface of the cap layer 5 was removed, an upper electrode 7 of Ti/Pt/Au was formed on the surface of the resulting structure, and a lower electrode 8 of AuGe/Ni/Au was formed on the back surface of the substrate 1.

Ins C57 After the substrate was then cleft into a bar with a different cavity length (L), a low-reflection film 9 of SiN was formed on one end face S_1 of the bar, and a high-reflection film 10 of SiO_2/Si was formed on the other end face S_2. Finally, the bar was worked into chips, whereupon devices, such as the one shown in FIG. 1, were obtained.

<u>2. Characteristics of Device</u>

For the devices obtained in this manner, injected currents (hereinafter referred to as kink currents) with which kinks are generated were measured.

Ins B1 The "kink" is defined herein as a state in which the external differential quantum efficiency of an oscillated laser beam is 15% or more, in consideration of the practicality of the device for use as a pumping light source.

FIG. 6 shows the results of measurement on the kink (a_1) that is attributable to jumping of longitudinal modes.

As seen from FIG. 6, the kink (a_1) current value of a device having the cavity length (L) of 800 μm is 200 mA, and that of a device having the cavity length (L) of 1,200 μm is 350 mA. In the case of a device having the cavity length (L) of 1,500 μm, however, currents not higher than 700 mA do not cause generation of the kink (a_1).

FIG. 7 shows the results of measurement on the kink (a_2) that is attributable to beam steering for the time of high current injection.

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As seen from FIG. 7, the kink (a_2) current value of the device having the cavity length (L) of 800 μm is 400 mA, that of the device having the cavity length (L) of 1,200 μm is 550 mA, and that of the device having the cavity length (L) of 1,500 μm is 700 mA. Thus, the greater the cavity length (L), the higher the current value that causes beam steering is.

This proves that if the cavity length (L) is longer, resistance heat attributable to the injected current is reduced correspondingly, so that the rise in temperature of the active layer can be restrained to ensure a satisfactory transverse light confinement effect by occurring no displacement of the transverse mode field.

In the case where the injected current is at 400 mA, operating voltages for the devices with the cavity lengths of 800 μm, 1,200 μm, and 1,500 μm are 2.1 V, 1.9 V, and 1.75 V, respectively. Thus, the greater the cavity length (L), the lower the operating voltage is.

FIG. 8 shows an oscillation spectrum of the device with the cavity length (L) of 1,500 μm for the case where the injected current is at 200 mA.

As seen from FIG. 8, this device is based on a longitudinal multi-oscillation mode in which a large number of longitudinal modes exist at short intervals in a gain band g. The interval between each two adjacent longitudinal modes is about 0.1 nm spacing.

FIG. 9 shows a current-optical output characteristic curve for this device.

In the case of this device, as seen from FIG. 9, injected currents not higher than 700 mA cause generation of no kinks, and the linearity of the current-optical output characteristic is maintained.

As is evident from the above description, the semiconductor laser device of the gain-waveguide type according to the present invention undergoes longitudinal multi-mode oscillation. In the module that is formed by connecting the device to the optical fiber, therefore, a bad influence of the return light can be restrained, and there is no possibility of dislocation of transverse modes (beam steering) in a far field pattern, so that fluctuations of the fetched optical output can be inhibited. In consequence, the linearity of the current-optical output characteristic can be maintained as a whole even if the injected current is increased.

Thus, the device according to the present invention, for use as a pumping light source for optical fiber amplifier, is of great industrial value.

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